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SAR Polarimetric Scattering from Natural Terrains

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Radar polarimetry and speckles of random rough surface scattering is studied using 3-D numerical solution of Maxwell equations (NMM3D) with surface size up to 32 32 squared wave- lengths. Proposed research is to model the rough surfaces which are characterized by exponential correlation functions.

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"SAR Polarimetric Scattering from Natural Terrains"

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Abstract :

Radar polarimetry and speckles of random rough surface scattering is studied using 3-D numerical solution of Maxwell equations (NMM3D) with surface size up to 32 × 32 squared wave- lengths. The rough surfaces are characterized by exponential correlation functions. The simulation results of cross- and co-polarization backscattering coefficients were in good agreement with experimental measurements of bare soils at L-band. Because in numerical solutions of Maxwell equations the electric fields of the scattered wave are calculated for each realization, scattering matrices can be simulated by NMM3D, and such simulations are performed in this paper. For a given RMS height, correlation length, soil permittivity, and incident angle, we calculated the radar scattering matrix up to 958 independent realizations. For each realization, the components of the scattering matrix, namely, S_{HH}, S_{VV}, S_{HV}, and S_{VH}, are calculated. Using the simulated scattering matrices, we calculate the polarimetric speckle statistics (amplitude and phase difference), followed by a comparison with theoretical distributions. For fully developed speckle from the homogeneous rough surface, the results are examined and vali- dated to ensure the simulated data quality as far as polarimetric properties are concerned. By taking ensemble averages, we calculate the coherency matrix from which the eigenvalues, entropy, anisotropy, and alpha angle in coherent target decomposition are then calculated. In particular, characterization of polarimetric descriptors for rough surface is presented. (IEEE Transactions on Geoscience and Remote Sensing, vol.52, pp. 7048-7058, 2014)

To compare with numerical model NMM3D, a physical model of rough surface scattering Advance Integral Equation Model (AIEM) is also investigated. To describe the completely scattering mechanism including single and multiple scattering, both single and multiple scattering expressions of AIEM are derived. The antenna pattern made in the derivation of AIEM are investigated for further improvements to close to the truly measurement situation. The completely Kirchhoff field coefficient, complementary field

coefficient and the traditional approximations of the Fresnel reflection coefficients are introduced in AIEM. The comparisons of the bistatic scattering behavior by using the improved AIEM is in excellent agreement with numerical simulation and measured data, in terms of angular, frequency and polarization dependences. Based on this model, a transition model for AIEM has been shown to improve the simulation accuracy. Validation by comparisons of the numerical method and experimental data gave good agreement. (IEEE Transactions on Geoscience and Remote Sensing, vol. 54, pp. 651-662, 2016) Furthermore, extension work to consider the bistatic scattering in more general, antenna patterns of the transmitter and receiver are accounted for their variations of overlapping illuminated area covering the targets of interest when the bistatic scattering configurations are changed. (PhD dissertation, K.L. Chen, 2015)

Introduction :

NMM3D is implemented by using the Method of Moment (MoM) to solve Maxwell equations. Fast method is implemented to accelerate the computation. Near-field precondition based on physical behaviors of electromagnetic field has been implemented to further accelerate NMM3D. With surface size of 16-by-$16\lambda^2$ with 16 points per wavelength, preconditioned NMM3D is more than 20 times faster than that without precondition. For a single realization, preconditioned case is close to 5 times faster. The preconditioned NMM3D are implemented in parallel using Message Passage Interface (MPI). We perform NMM3D simulations using CPU cores on NSF XSEDE (Extreme Science and Engineering Discovery Environment) clusters.

The preconditioned NMM3D were performed with 256 CPU cores on NSF XSEDE Stampede (2.7GHz Xeon E5-2680 CPU) clusters. NMM3D gives results of the complex electric fields of the scattered wave. Because a finite surface size is used in the simulations, we compute the incoherent scattering field by subtracting the coherent field from the total. The coherent field is first obtained by averaging the scattered electric field over many realizations. The normalized scattering matrix for n-th realization is by

$$S_{\beta\alpha,n} = \sqrt{\frac{1}{2\eta P_{\alpha}^{inc}}\cos\theta_i}\, E_{\beta\alpha,n}^{incoh}$$

In the backscattering direction, the coherency matrix is calculated by.

$$\bar{k} = [k_1 \quad k_2 \quad k_3]^T = \frac{1}{\sqrt{2}}[S_{VV} + S_{HH} \quad S_{VV} - S_{HH} \quad 2S_{VH}]^T$$

$$\bar{\bar{T}}_3 = \langle \bar{k}\bar{k}^{\dagger} \rangle = \begin{bmatrix} \langle k_1 k_1^* \rangle & \langle k_1 k_2^* \rangle & \langle k_1 k_3^* \rangle \\ \langle k_2 k_1^* \rangle & \langle k_2 k_2^* \rangle & \langle k_2 k_3^* \rangle \\ \langle k_3 k_1^* \rangle & \langle k_3 k_2^* \rangle & \langle k_3 k_3^* \rangle \end{bmatrix}$$

The eigen-values and eigen-vectors from ensembled coherency matrix are then adopted for the coherency matrix polarimetric descriptors, including entropy (*H*), anisotropy (*A*), and alpha angle (α). Where p_i denotes the eigen-value fraction and $\lambda_1 > \lambda_2 > \lambda_3$; α_i is extracted from unitary eigen vectors of coherency matrix.

$$p_i = \frac{\lambda_i}{\sum_{i=1}^{3}\lambda_i}$$

$$H = -\sum_{i=1}^{3} p_i \log_3 p_i$$

$$A = \frac{p_2 - p_3}{p_2 + p_3}$$

$$\alpha = \sum_{i=1}^{3} p_i \alpha_i$$

For the physical model, electromagnetic waves scattering from a randomly rough surface is importance in many fields of disciplines but complex and sometimes intricate mathematical derivations. To remain a high level of accuracy and reduce the burden of mathematical derivations, some proposed methods have been developed by dropping off some terms which unavoidably degraded the model accuracy. Driven by the need of predicting bistatic scattering and microwave emissivity, many efforts have been devoted to further improving the accuracy by removing some of the assumptions. The introduction of a transition function into the Fresnel reflection coefficients takes spatial dependences into account. It can remove the restrictions on the limits of surface roughness and permittivity, and work perfectly for a broad range of surface dielectric and geometric parameters.

The Fresnel reflection coefficients for horizontally and vertically polarized wave are:

$$R_h = \frac{\mu_t k \cos\theta_i - \mu_0 k_{tz}}{\mu_t k \cos\theta_i + \mu_0 k_{tz}}, \qquad R_v = \frac{\epsilon_0 k_{tz} - \epsilon_t k \cos\theta_i}{\epsilon_0 k_{tz} + \epsilon_t k \cos\theta_i}$$

where $k_{tz} = \mathrm{Re}\{k_{tz}\} + j\,\mathrm{Im}\{k_{tz}\}$

and

$$\mathrm{Re}\{k_{tz}\} = \frac{1}{\sqrt{2}}\left[\mathrm{Re}\{k_t^2\} - k^2\sin^2\theta_i + \sqrt{\left(\mathrm{Re}\{k_t^2\} - k^2\sin^2\theta_i\right)^2 + \left(\mathrm{Im}\{k_t^2\}\right)^2}\right]^{1/2}$$

$$\mathrm{Im}\{k_{tz}\} = -\frac{1}{\sqrt{2}}\left[\left(\mathrm{Re}\{k_t^2\} - k^2\sin^2\theta_i\right) + \sqrt{\left(\mathrm{Re}\{k_t^2\} - k^2\sin^2\theta_i\right)^2 + \left(\mathrm{Im}\{k_t^2\}\right)^2}\right]^{1/2}$$

With Geometric Optics model (GOM) as a reference, it is observed that the difference between the use of original transition model and updated one in AIEM becomes larger as the surface dielectric decreases, and the transition model has more impact on the vertical polarization than on horizontal polarization. With the Fresnel transition model, the azimuthal angular behavior of AIEM matches perfectly that of GOM.

Results and Discussion :

(1) Polarimetric Simulations of SAR at L-Band Over Bare Soil Using Scattering Matrices of Random Rough Surfaces From Numerical Three-Dimensional Solutions of Maxwell Equations (IEEE Transactions on Geoscience and Remote Sensing, vol.52, pp. 7048-7058 (2014))

We have applied NMM3D as a PolSAR simulator for L-band incident on random rough soil surface. In NMM3D, there are no priori assumptions of radar cross sections or speckle statistics. We generate a sample of random rough surface and then use numerical solution of Maxwell equations to calculate the scattering matrices, namely, S_{HH}, S_{VV}, S_{HV}, and S_{VH}, for each sample. For a given RMS height, correlation length, and soil permittivity and for a given incident angle, we calculated the scattering matrix up to 958 realizations. Using the ensemble of simulated scattering matrices, the polarimetric speckle statistics (amplitude and phase difference) are calculated and examined. It is confirmed that the simu- lated data fully agreed with theoretical Wishart distributions for homogeneous rough surface. By taking ensemble averages of combinations of scattering matrix elements, the coherency matrix is calculated. In the characterization of three polarimetric descriptors, H increases as roughness increases, which means that more depolarization occur, whereas A displays a nonlinear effect versus ks—it increases for small values of ks and turns to decrease when ks further increases, implying that the relationship between anisotropy and surface roughness is not linear. We also observe that the alpha angle is not so sensitive to ks, as expected. It would be highly suggestive that, by saying that the surface is smooth or rough, special attention must be paid. From our simulation study, it is found that even for a small set of kl and ks, significant depolarization due to multiple scattering may occur in an exponentially correlated surface. Scattering symmetry, including reflection, rotation, and azimuthal symmetries, is also investigated. For the exponentially correlated surface, even for small roughness scale, conditions of reflection symmetry generally are not met. We also describe the NMM3D methods of SAR simulations, noting that the cross polarizations were in good agreement with experimental data. The accuracy of cross polarization is an important criterion for a PolSAR simulator. In the simulations in this paper, each realization of random rough surface is independent of the other. Finally, it would be both theoretically and practically interesting to study the effect of the dielectric properties (or soil moisture content). Investigating the assumptions made in well-known parameter inversion algorithms from PolSAR data should be also explored.

(2) Copolarized and Cross-polarized Backscattering from Random Rough Soil Surfaces from L-band to Ku-band Using Numerical Solutions of Maxwell's Equations with Near Field Precondition (IEEE Transactions on Geoscience and Remote Sensing, vol. 54, pp. 651-662 (2016))

We introduce the near-field precondition method to NMM3D, and it provides faster and consistent simu- lation time that is independent of roughness. This will be useful as we move forward to larger roughness and larger surface size. In addition, we extend the study of backscattering from soil rough surface from L-band to C-, X-, and Ku-bands. We cross compare various models for copolarization, cross-polarization, and polarization ratio, HH/VV. Frequency dependence, incident angle dependence, and soil moisture dependence are applied to examine these quantities. We also use measurement data from POLARSCAT data-1 to validate these models. In model comparison, measurement-data-based empirical model, Oh's model, is treated as reference to see how model results are close to measurement for L-, C-, and X-bands. We notice NMM3D performs pretty well considering all the concerned quantities. We then emphasize on the polarization ratio, i.e., HH/VV, at the last part of this paper. In the frequency dependence plot, we notice the difference among models. We explain some inherent properties of SPM, which causes no dependence on surface roughness. This leads to no dependence on frequency. Among these models, NMM3D agrees well with Oh's model from L- to Ku-bands. This suggests that HH/VV could be a good estimate to be included for the soil moisture retrieval study of land surfaces. In addition, NMM3D will also be useful for C-, X-, and Ku-bands. NMM3D results will also be implemented in the NASA Earth Observing System Simulator Suite (NEOS3) platform for the research community to study land surface.

(3) Multiple Scattering Effects with Cyclical Terms in Active Remote Sensing of Vegetated Surface Using Vector Radiative Transfer Theory (IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 9, pp. 1414-1429 (2016))

The multiple scattering and backscattering enhancement effects on volume scattering with the existence of one bottom reflective boundary are considered by applying the iterative numerical approach to solve the vector RT equation. The optical thickness dependence, frequency dependence, and angular dependence of backscattering are considered in the analyses.
Multiple scattering effects are important when the optical thickness and the scattering albedo are large. We notice that when both the albedo and the optical thickness exceed 0.4, higher orders start to contribute significantly. For L-band, the deviation between first order and multiple scattering for VV backscattering is larger than that of HH and could be 3.5 dB when VWC is 3 kg/m2. Dominant scattering orders and mechanisms are identified. Multiple scattering effects contribute significantly to both VV and HH polarizations rather than only VV for L-band. This would be essential for C-, X-, and Ku-bands, since the underestimated backscatters caused by the attenuation could be corrected by multiple scattering.
The cyclical correction resulting from backscattering enhancement effects makes copolarized backscatters from RT approach agree those from the wave approach. Extensive validation of multiple scattering model using an a priori lookup table of corn fields with SMAPVEX12 measurement data was performed. Good agreement for both the forward copolarization comparison and time-series soil moisture retrieval are achieved. Multiple scattering model is also applied to time-series soil moisture retrieval in NASA SMAP mission.

(4) Simulations of scattering matrix and coherency matrix for Pol-SAR applications of soil and vegetated surfaces using 3-D numerical solutions of Maxwell equation (NMM3D) (IEEE International Geoscience and Remote Sensing Symposium (IGARSS), 2015)

Scattering matrices (S_{HH}, S_{VV}, S_{HV}, and S_{VH}) are calculated from numerical 3D solutions of Maxwell equations (NMM3D). Using the simulated scattering matrices, we compute the polarimetric speckle and the coherency matrix for Pol-SAR applications. Results from NMM3D are examined by the comparison with theoretical distributions, including amplitude, phase difference, and amplitude ratio. Surface roughness dependence with entropy, anisotropy, and alpha angle from the ensemble average of coherency matrix is also studied. In this paper, we calculate polarimetric statistics of rough surface at C-band (5.4GHz) with 40 degree incidence. Scattering matrices and coherency matrix for rough surface were computed for various rms height, 1cm-4cm, at C-band (5.4GHz). Polarimetric descriptors were studied and higher entropy at C-band causes data located mostly in random surface region on H-α classification plane.

(5) New expressions for multiple scattering of AIEM (Doctoral Dissertation, K.L. Chen)

The expressions for multiple scattering terms are re-derived to gain more physical insights into the field interactions, and the scattering coefficient is written as a sum of three terms: the Kirchhoff term, the cross term due by the Kirchhoff field and complementary field, and the complementary term. The complementary scattered field, propagating upward and downward and the each upward or downward include the re-radiated wave in medium 1 or medium 2. All four components of the propagation directions are considered, upward-upward, upward-downward, downward-upward, and downward-downward. For the integration process, the variables of phase term can be calculated such as Fourier integral formulation, and two delta functions will be generated by the integral process. And then, a group of surface spectrum variables can be simplified by integral with the delta functions. Finally, the only a pair of surface spectrum need to calculate by numerical integration.

(6) Antenna Pattern Effects on Rough Surface Scattering (Doctoral Dissertation, K.L. Chen)

Many researches show that the antenna pattern is an important parameter for ground base measurements, but consider the scattering models as plane wave incident, tapered wave pattern and a match phase center. Under the assumption of Gaussian pattern and the transmitting and receiving antenna patterns are un-matched, the relative importance of the antenna parameters as well as the Fresnel term in scattering coefficient in the scattering field expression are examined. And the scattering coefficient is derived under Kirchhoff approximation. The Gaussian antenna beam effect is discussed on coherent scattering coefficient. Some special cases of antenna patterns are investigated.

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d) conference presentations without papers
e) manuscripts submitted but not yet published, and
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a) papers published in peer-reviewed journals, dissertation

[1] **Doctoral Dissertation Title :** Polarimetry In Radar Backscattering from Soil and Vegetated Surfaces
Institution : University of Washington, Seattle, Washington, USA
Date : 2015
Authors : Tien-Hao Liao

[2] **Doctoral Dissertation Title :** Modeling of Electromagnetic Wave Scattering for Rough Surface, Doctoral Dissertation
Institution : National Central University, Zhongli, Taiwan
Date : 2015
Authors : Kuan-Liang Chen

[3] **Journal name :** IEEE Transactions on Geoscience and Remote Sensing, vol. 54, pp. 651-662 (2016)
Title : Copolarized and Cross-polarized Backscattering from Random Rough Soil Surfaces from L-band to Ku-band Using Numerical Solutions of Maxwell's Equations with Near Field Precondition
Date : 2016/2/2
Authors : T.-H. Liao, L. Tsang, S. Huang, N. Niamsuwan, S. Jaruwatanadilok, S.-B. Kim, H. Ren, and K.-L. Chen

[4] **Journal name :** IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol.9, pp. 272-284 (2016)
Title : Coherent Model of L-Band Radar Scattering By Soybean Plants: Model Development, Validation and Retrieval
Date : 2016/1/1
Authors : H. Huang, S.B. Kim, L. Tsang, X. Xu, T.H. Liao, T. J. Jackson, and S. Yueh

[5] **Journal name :** IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 9, pp. 1414-1429 (2016)
Title : Multiple Scattering Effects with Cyclical Terms in Active Remote Sensing of Vegetated Surface Using Vector Radiative Transfer Theory
Date : 2016/4/4
Authors : T.-H. Liao, S.-B. Kim, S. Tan, L. Tsang, C. Su, T. J. Jackson

[6] **Journal name :** IEEE Transactions on Geoscience and Remote Sensing, vol.52, pp. 7048-7058 (2014)
Title : Polarimetric Simulations of SAR at L-Band Over Bare Soil Using Scattering Matrices of Random Rough Surfaces From Numerical Three-Dimensional Solutions of Maxwell Equations
Date : 2014/11/11
Authors : K.-S. Chen, L. Tsang, K.-L. Chen, T.-H. Liao, and J.-S. Lee

[7] **Journal name :** IEEE Transactions on Geoscience and Remote Sensing, vol.52, pp. 1381-1396 (2014)
Title : Models of L-band radar backscattering coefficients over the global terrain for soil moisture
Date : 2014/2/2
Authors : S.-B. Kim, M. Moghaddam, L. Tsang , M. Burgin, X. Xu and E.G. Njoku

[8] **Journal name :** IEEE Transactions on Geosceince and Remote Sensing, vol.52, pp. 5966-5973 (2014)
Title : A Simulation Study of Compact Polarimetry for Radar Retrieval of Soil Moisture
Date : 2014/9/9
Authors : J. D.Ouellette, J. T. Johnson, S. B. Kim, J J. Van Zyl, M. Moghaddam, M. Spencer, L. Tsang, and D. Entekhabi

b) papers published in peer-reviewed conference proceedings

[1] **Conf. proceedings name :** EUSAR 2014; 10th European Conference on Synthetic Aperture Radar; Proceedings of
Title : Soil moisture retrieval using L-band time-series SAR data from the SMAPVEX12 experiment
Date : 2014/7/17

Authors : S.-B. Kim, H. Huang, L. Tsang, T. Jackson, H. McNairn, J. V. Zyl

[2] **Conf. proceedings name :** IEEE International Geoscience and Remote Sensing Symposium (IGARSS), 2014

[3] **Title :** Coherent model of L band radar scattering by soya bean fields using analytic methods and Monte Carlo simulations
Date : 2014/11/6
Authors : H. Huang, X. Xu, L. Tsang

[4] **Conf. proceedings name :** General Assembly and Scientific Symposium (URSI GASS), 2014 XXXIth URSI
Title : Multiple scattering effects with inclusion of cyclical terms in radar scattering of vegetated surfaces using vector radiative transfer theory
Date : 2014/10/20
Authors : S. Tan, L. Tsang, S.-B. Kim

[5] **Conf. proceedings name :** IEEE International Geoscience and Remote Sensing Symposium (IGARSS), 2015
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Authors : T.-H. Liao, L. Tsang

c) papers published in non-peer-reviewed journals and conference proceedings

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[2] **Conference name :** IEEE International Symposium on Antennas and Propagation & USNC, Vancouver, Canada
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Date : July, 2015

[3] **Conference name :** IEEE Geoscience and Remote Sensing Symposium, Milan, Italy
Title : L-BAND RADAR SCATTERING OF WHEAT AND CANOLA FOR SMAP APPLICATIONS
Date : July, 2015

[4] **Conference name :** IEEE Geoscience and Remote Sensing Symposium, Milan, Italy
Title : Simulations of Scattering Matrix and Coherency Matrix for Pol-SAR Applications of Soil and Vegetated Surfaces using 3-D Numerical Solutions of Maxwell Equation (NMM3D)
Date : July, 2015

[5] **Conference name :** IEEE Geoscience and Remote Sensing Symposium 2016, Beijing, China
Title : Muptiple Scattering Effects in Vegetated Surfaces and Rough Surface Boundary Condition at C-band for Remote Sensing of Soil Moisture
Date : July, 2016

[6] **Conference name :** IEEE Geoscience and Remote Sensing Symposium 2016, Beijing, China
Title : Combined Active and Passive Microwave Remote Sensing of Soil Moisture for Vegetated Surfaces at L-band
Date : July, 2016

[7] **Conference name :** Progress In Electromagnetics Research Symposium, Guangzhou, China
Title : Active and Passive Remote Sensing of Bare Soil from L-band to Ku-band Using NMM3D
Date : August 2014

[8] **Conference name :** Progress In Electromagnetics Research Symposium, Guangzhou, China
Title : Polarimetric Properties of Randomly Rough Surfaces at L-band Using Numerical 3D Solutions of Maxwell Equations
Date : August 2014

[9] **Conference name :** AGU, San Francisco, USA
Title : NASA Earth Observing System Simulator Suite (NEOS3): a Forward Simulation Framework for Observing System Simulation Experiments
Date : December 2014

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f) provide a list any interaction with industry or with Air Force Research Laboratory scientists of significant collaborations that resulted from this work

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[2] **Name :** Calibration and Validation in Active and Passive Microwave Remote Sensing of SMAP Based on Physical Models for Improved Algorithm Performance, PI : Leung Tsang
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